# Emission Control Strategies for PM and NOx or What is the prognosis for HDD 0.2 g/bhp-hr NOx and 0.01 g/bhp-hr PM?

Tim Johnson

Corning Incorporated

February 18, 2000



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## The outlook is good, but not without issue

- PM
  - Filters are very efficient (99.9% on particles, 80%+ by mass)
  - low sulfur fuel will be needed (<20 ppm)
- NOx is more difficult
  - 80+% efficiency emission control plus EGR will hit
  - SCR will happen in Europe and can hit 80+%
  - NOx traps are emerging
    - very low sulfur may be needed
- Integrated systems are SO CLOSE

***Give us a market, and "THEY WILL COME"***



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# Agenda

- Emerging US and European Regulations
- Overview of PM Technologies
- Overview of NOx Control Technologies
- Pulling it all Together



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# Emerging Regulations



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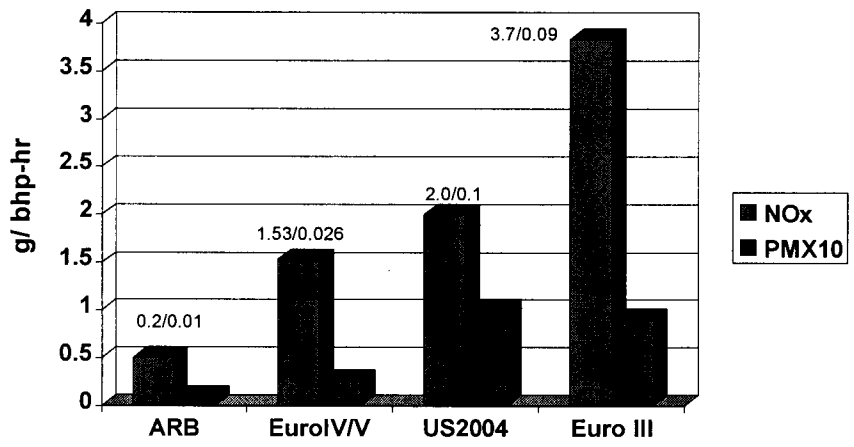
## Euro IV/V is the tightest officially proposed regulation; ARB 0.2/0.01 is about 60 to 87% tighter




- Adjusted for transient test differences
- ARB is from the transit bus proposal



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## Engine technologies and emissions



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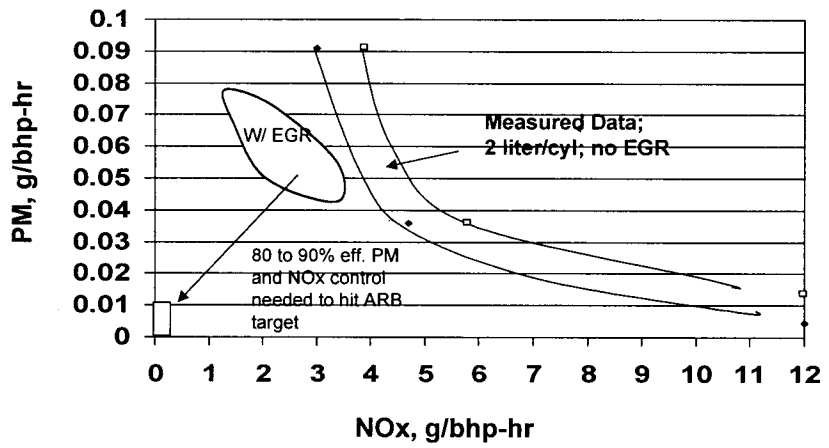
## State-of-the-art engines will need 80% efficient PM and NOx emission control




Data from Moser, AVL, May 1999



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## Engine Modeling at the Univ. of Wisconsin Results in a "Virtual Engine"

Parameters of Interest and Ranges of Variation

| | |
|---|---|
| •Boost Pressure (kPa) | 165 ⇨ 284 |
| •EGR (%) | 0 ⇨ 50 |
| •SOI (CA deg. atdc) | -10 ⇨ +10 |
| •Injection Pressure (MPa) | 100 ⇨ 200 |
| •Mass in First Pulse (%) | 10 ⇨ 90 |
| •Dwell (CA deg.) | 5 ⇨ 15 |

Physical Constraints on the Engine

- •Maximum Exhaust Temperature of 1023 K
- •Maximum Peak Pressure of ~ 15 MPa

Rolf Reitz, Univ. Wisconsin, 9/99



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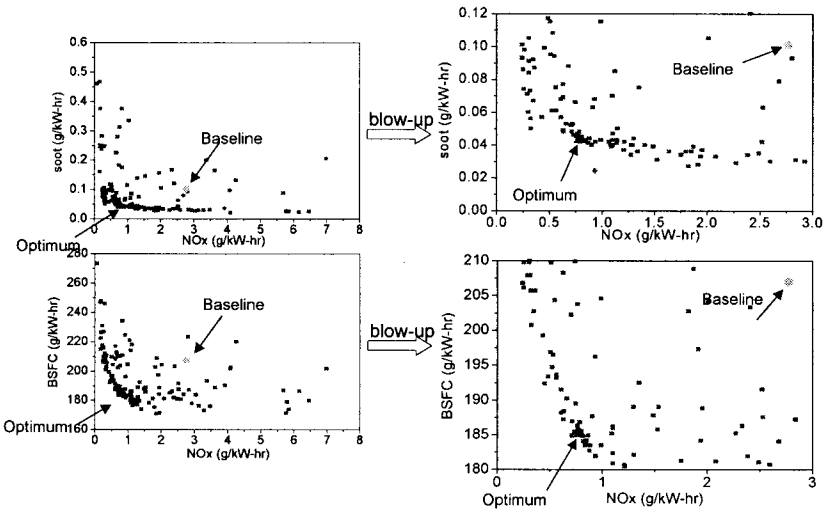
## With changes in standard engine operating parameters, the *virtual* engine can achieve 0.4 g/bhp-hr NOx and 0.05 g/bhp-hr PM




Rolf Reitz, Univ. Wisconsin, 9/99



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## Although there's much gap between the virtual and the real engines, the potential for improvement can not be denied.

- HDD fuel injection technology is still gaining
- Fuel benefits have yet to be realized
- Computer modeling has just reached the point where significant fundamental understanding can now be obtained
- Actual laser observation of combustion is yielding impressive results and confirmation of models
- Feedback control of diesel engines is emerging
- NOx and engine sensors are emerging
- Variable valve timing is untapped
- New materials are emerging
  - composites
  - MEMS

**"Diesel engine technology is in its adolescence, at best."**
Prof. Tony Oppenheim; UC, Berkeley; Member NAE; FIC



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## Advancements in Diesel Particulate Traps



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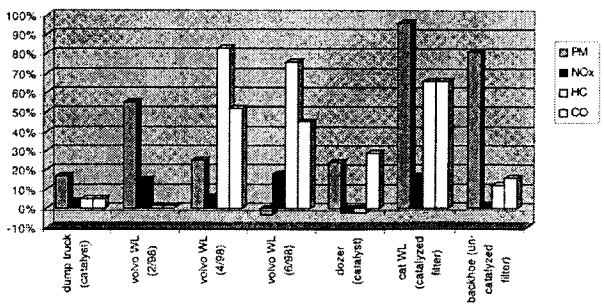
## Retrofitting Off-Road Diesel Equipment with DOC & DPF Significantly Reduced Emissions




| | DOC | DPF |
|---|---|---|
| **PM** | -3 to 50%<br>20% typ. | 80-95% |
| **NOx** | 0-17%<br>12% typ. | 2-15% |

Nescaum SAE 1999-01-0110

Emissions reductions from DPF and oxidation catalysts depend on the equipment



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## The VERT Study on LDD & Off Road HDD Showed DPF's Significantly Reduce PM and Gaseous Emissions

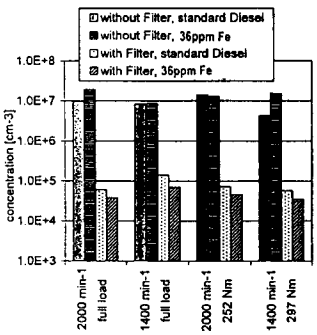


**Fig. 14:** Concentration count integrated in the range 20 - 200 nm

Filters reduced PM by more than 99% by number at all load points

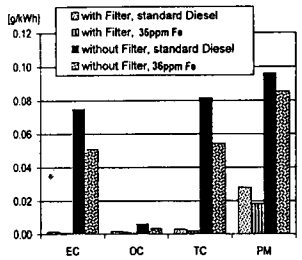


**Fig. 15:** CAT4 filter function according to Coulometry

Only the newer sensor technology [7] facilitates particulate counting during transients. The results confirm that filtration rates of 99% and more can be attained under transients, too.

Filters reduced PM by 99%+ by number, but only 70% by mass

EC: elemental C
OC: organic C

Sponsors: Swiss & Austrian Accident Insurance Agencies, German Association of Construction Professionals, Swiss EPA

VERT SAE 1999-01-0116



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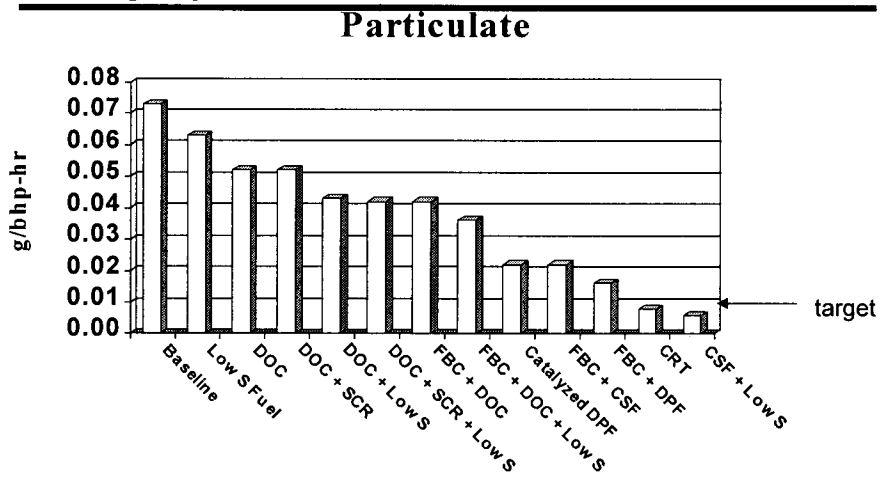
## Diesel filters allowed a 0.07 g/bhp-hr engine to hit 0.01 g/bhp-hr PM




MECA study - 1999
12.7 L Heavy Duty Engine
Detroit Diesel Series 60

DOC: Diesel oxidation catalyst
SCR: Selective catalytic reduction
FBC: Fuel-borne catalyst
CRT: Continuous regenerating technology
CSF: Catalyzed soot filter



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## The DECSE study showed that 20 ppm or lower sulfur is needed to hit 0.01 g/bhp-hr

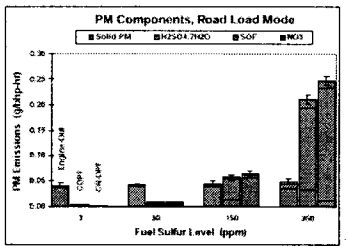
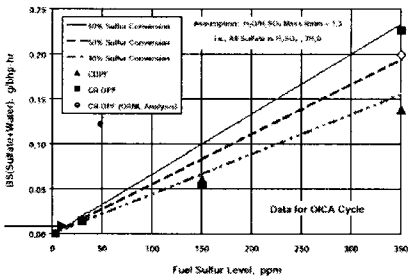



Figure 3.2-4. PM composition as a function of fuel sulfur level, for road-load mode (with 95% confidence intervals for average PM emissions)




At 3 ppm sulfur, trap PM efficiency is 94%; at 30 ppm sulfur, 74%. At higher sulfur levels, PM goes up! Sulfates are the culprits.

The lines are theoretical relationships between sulfate production and fuel sulfur levels. To get less than 0.01 g/bhp-hr, less than 20 ppm sulfur is needed.

From DOE website; Diesel Emission Control - Sulfur Effects;
Sponsored by DOE, EMA, MECA, and National Labs



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## What about filter regeneration?



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# CRT System is very effective, but requires low-S fuel and min. NOx/C

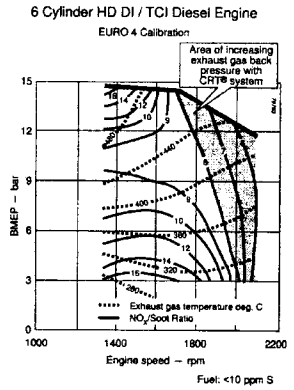


Fig. 17: Exhaust Gas Temperature and $NO_x$/Soot Ratio in Load-Speed Map of EURO 4 Engine with CRT System

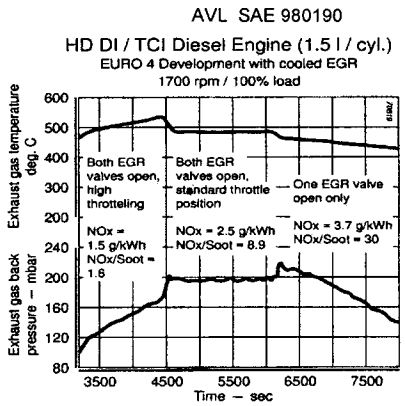


Fig. 18: Loading and Regeneration Behaviour of a CRT System

A minimum NOx/PM ratio of 8:1 was determined to be needed for CRT operation. It is generally available over most of the operating range.



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## Success DPF Regeneration of an IDI 2.5l engine was accomplished using cerium fuel additives and engine throttling to increase exhaust T

Such a regeneration process supported by throttle operation is shown as an example in Fig. 13.

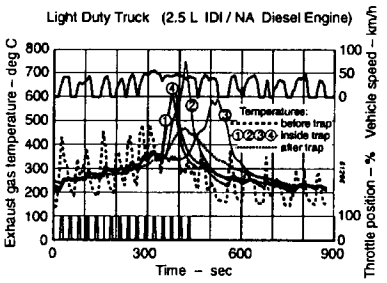


Figure 13. Regeneration Process Supported by Throttle Operation in 2nd Phase of FTP 75

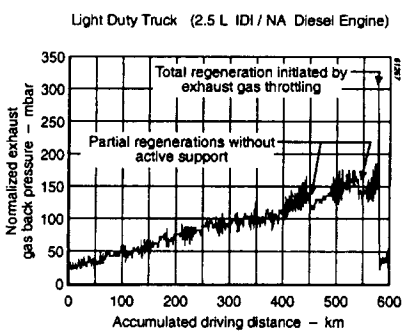


Figure 14. Trap Loading and Regeneration Events during Real Inner-City Vehicle Operation

Periodic throttling of inlet air was used to regenerate a fully loaded DPF by increasing T. Cerium additions to fuel were 100 ppm

Method was successfully used in real inner city driving

AVL, RHODIA, Renault SAE 982598

- Cerium dropped regeneration T from 560° to 300°C
- 50 ppm additions are described in recent literature



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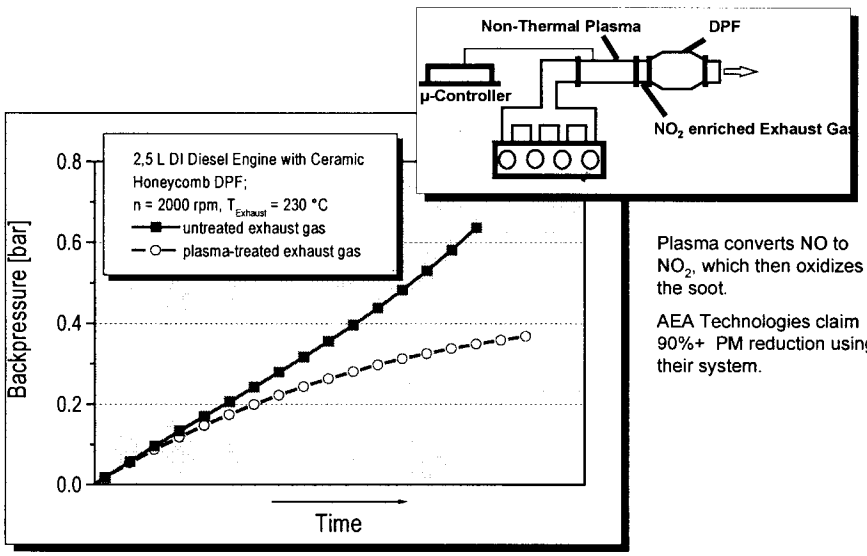
## Non-thermal plasma is emerging as a potential PM and perhaps NOx emission control system




Plasma converts NO to $NO_2$, which then oxidizes the soot.

AEA Technologies claim 90%+ PM reduction using their system.



Geckler, EEV, 9-99

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## Other recently reported regeneration schemes

- Active fuel management
  - Peugeot will post inject fuel and burn it in a DOC to generate heat; cerium catalyst added to fuel
- Microwave
  - need low mass filter, but some results on heating only soot



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# NOx Treatment



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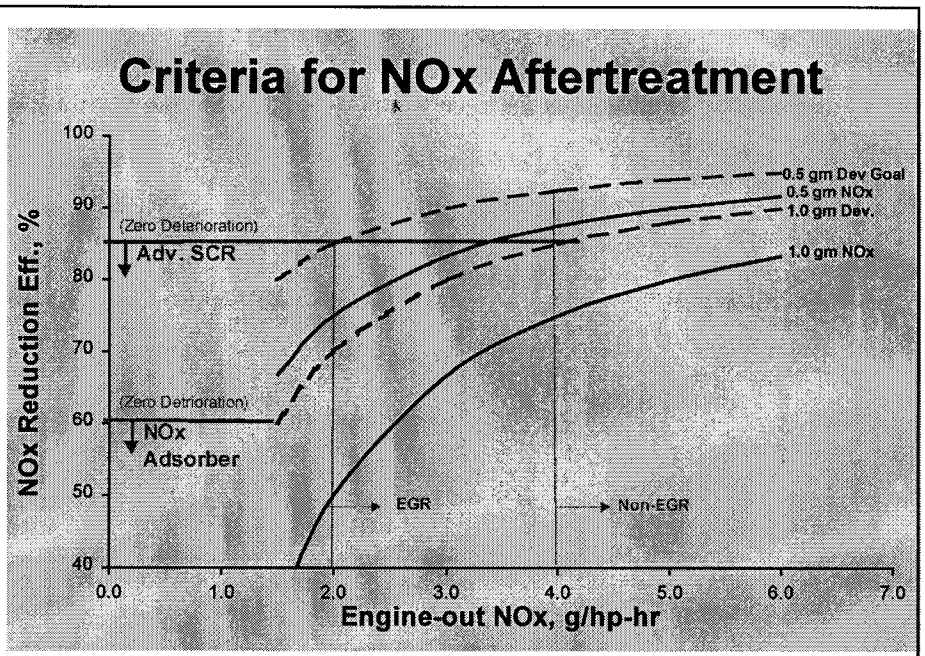


Liang, Caterpillar, 9-99



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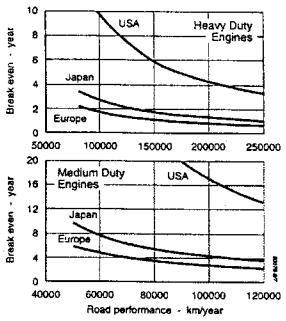
# Europe is moving towards SCR: win/win/win (5% better fuel economy and clean air)

- 85% efficient SCR allows early injection. This saves 5% on fuel consumption vs. cooled EGR options; pay back is 1 year in Europe and 6 years in US
- To hit 0.5 g/bhp-hr NOx and 0.01 g/bhp-hr PM (shown as shaded box), late injections would be needed to balance filters, SCR and EGR, losing the fuel savings.



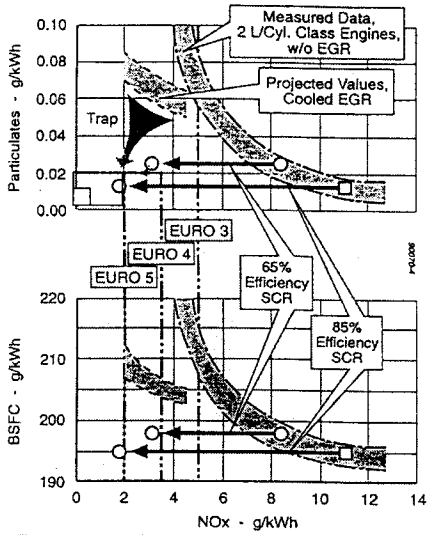




Fig. 4: Emissions / Fuel Consumption Strategies

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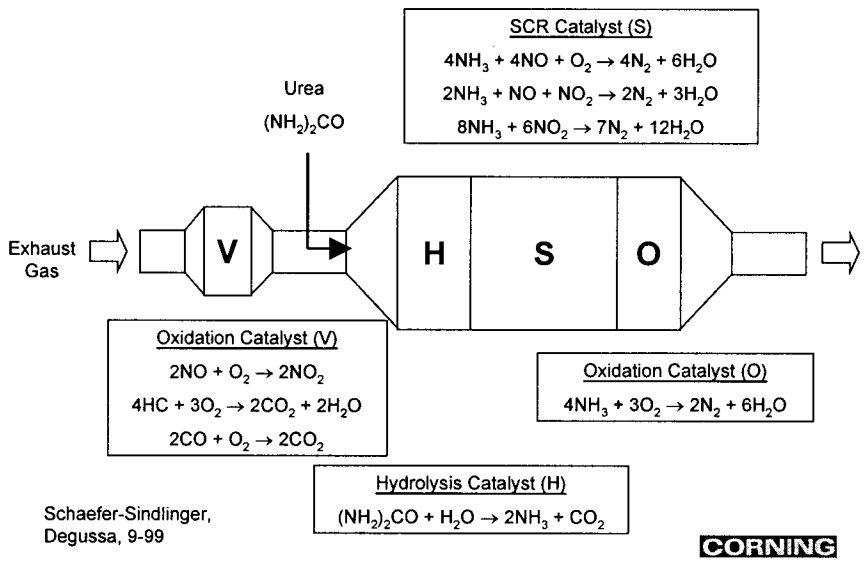
# State-of-the Art SCR system has NO2 generation and oxidation catalyst to eliminate ammonia slip




Schaefer-Sindlinger, Degussa, 9-99

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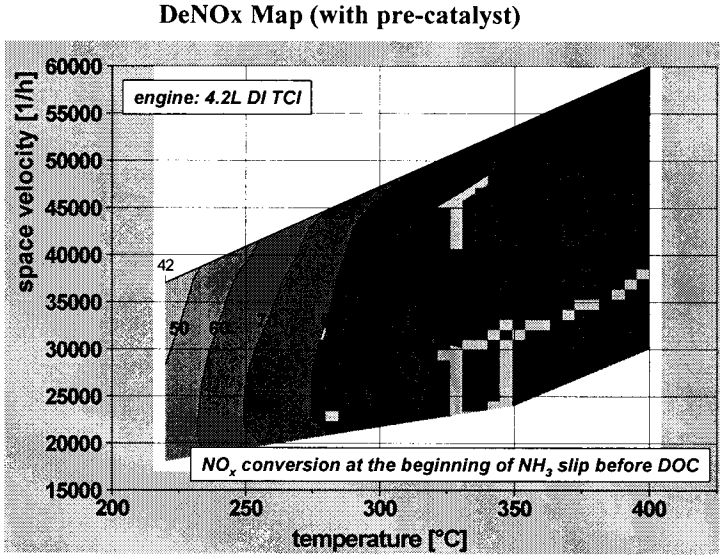
## SCR systems can hit 80+% efficiency under reasonable conditions, and improving

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Engine dyno work; Schaefer-Sindlinger, Degussa 9-99

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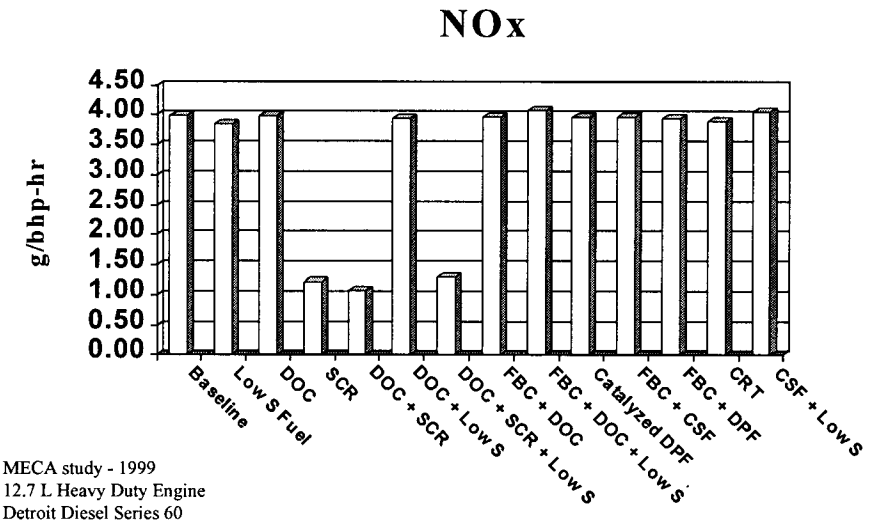
## SCR hit 75% efficiency without EGR




MECA study - 1999
12.7 L Heavy Duty Engine
Detroit Diesel Series 60

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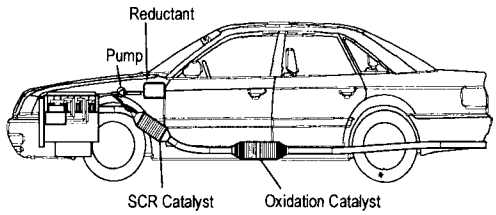
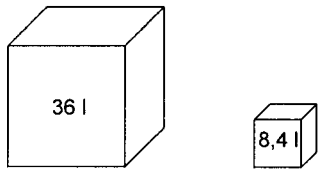
## *Much work is proceeding on addressing urea volume and distribution issues using solid urea*




Reductant required for 30.000 km Mileage(NOx Conversion approx.. 65 %):




Geckler, FEV, 9-99



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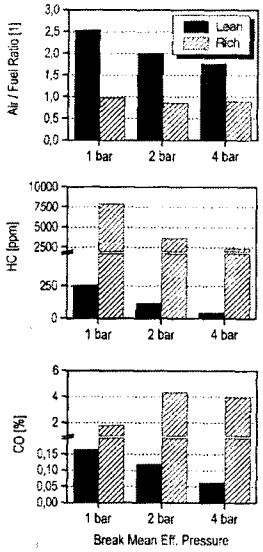
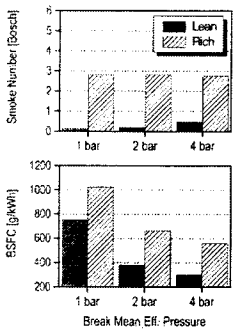
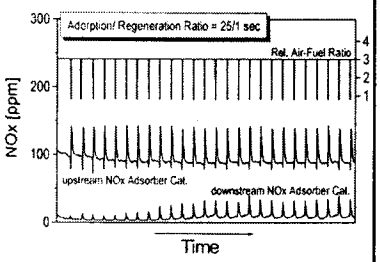
## NOx Traps are Evolving for Diesel




91% NOx eff. at 2000 rpm/2 bar

Diesel engines can be run rich enough to desorb NOx traps, with only 2% penalties in smoke & fuel efficiency

FEV SAE 1999-01-0108



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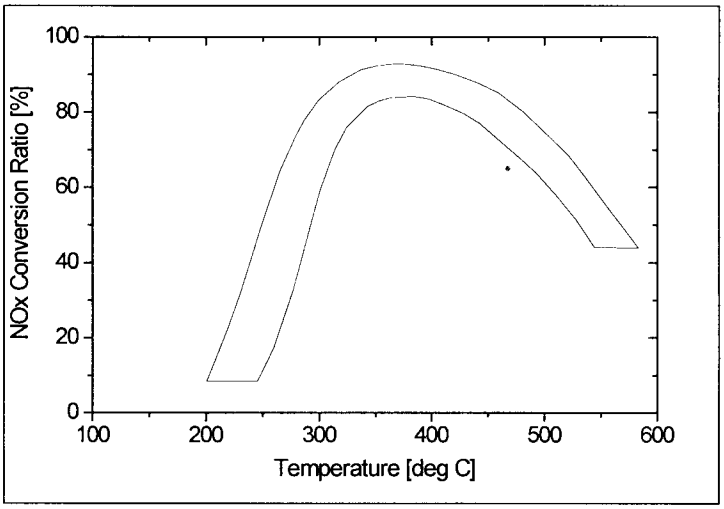
## *$NO_x$ Adsorber conversion ratios are getting into the high-80% efficiencies at reasonable, but still high, temperatures*




Geckler, FEV, 9-99



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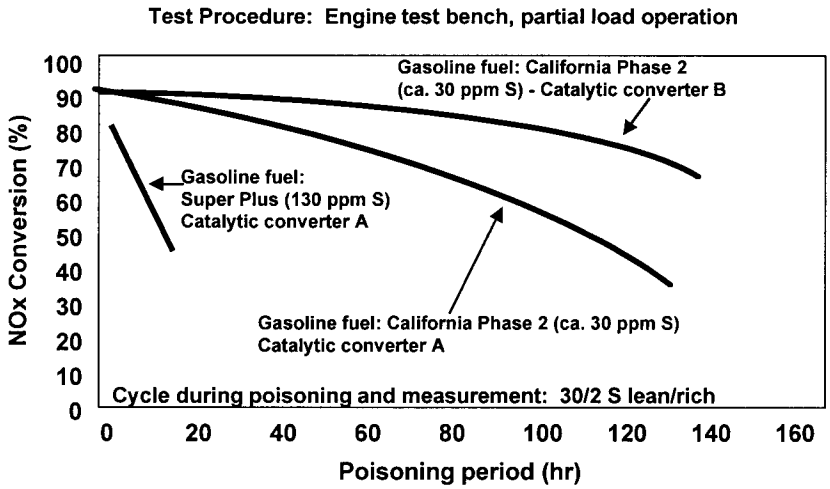
## *Advances are being made in NOx Adsorber Sulfur Resistance*




Quissel et al, VDA-Fortschrittsberichte, 12 (348), Bd. 2, 225-246 (1998)

From Bailey, ASEC, 9-99



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## First results on NOx traps for light-duty diesel show that less than 10 ppm sulfur in the fuel may be required

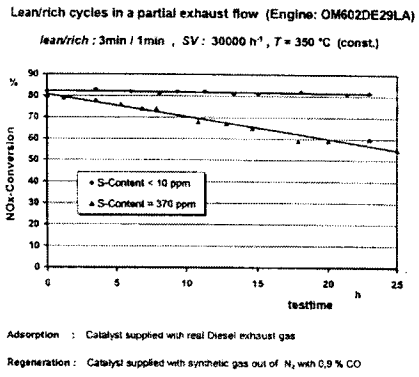


Figure 8: Aging of the NOx-storage-catalyst in a partial exhaust flow by sulphur

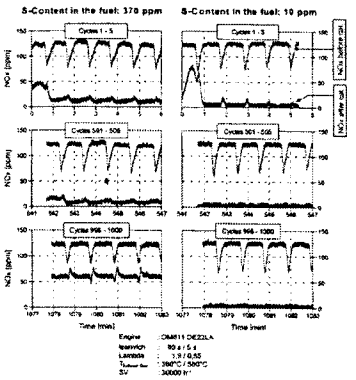


Figure 10: Sulphur-aging of a NOx-storage catalyst by lean/rich cycles in the real diesel exhaust gas engine

Laboratory results.

Engine results show minimal sulfur effects after 1000 regeneration cycles with 10 ppm fuel



DaimlerChrysler SAE 1999-01-1328

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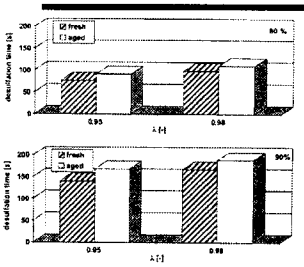
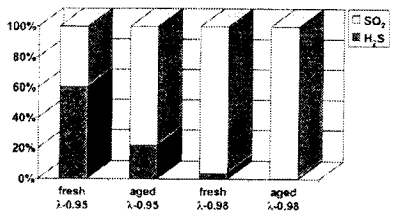
## Sulfur Purging of NOx Traps is Characterized and May Lead to Strategies that can Remediate 105 ppm S (*gasoline*)

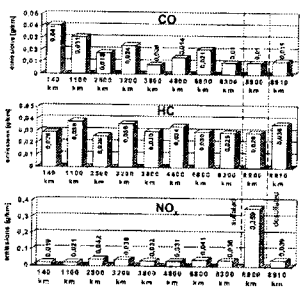



Time to reach 80 & 90% desulphuration in rich exhaust at 650°C




Degussa SAE1999-01-1285

A/F control and switching frequency can be used to affect desorbed sulfur species




On-road test results before and after sulphation of NOx trap - **IT WORKS!**

- Mapping of rich desulphation characteristics yields an engine management game plan
- Results are encouraging

**Desulphation is much more difficult in diesel (low temperatures and leaner)**



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# Wrap-Up



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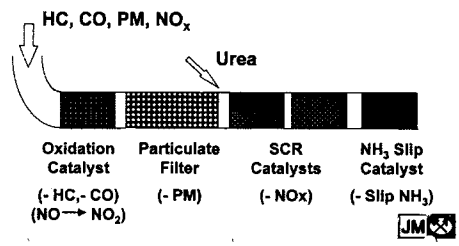
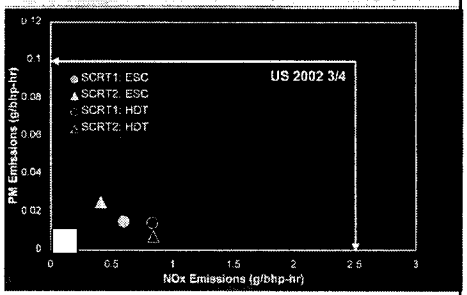
# System integration to get 0.2/0.01: Coming close, so "stay tuned"

*SCRT™ Schematic*




*SCRT™ Performance over the OICA and HDT Cycles (Low Mileage)*




One concept of an integrated PM and NOx system is in testing in Europe and elsewhere.

The system is close to achieving the target of 0.2/0.01 (NOx/PM, g/bhp-hr). Further optimization will help.

Cooper, Joyhnson-Matthey, 9-99



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## On the filter side, there are issues that are still being resolved, but much progress is being made

- Filter regeneration
  - passive or transparent
  - fuel minimized
  - catalyst enhanced
- Durability
  - related to regeneration and flow control
  - New filter configurations and HT materials being developed
- Back pressure
- Sulfur needs to be less than 20 ppm



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## NOx systems have come a long way and are close

- SCR will hit the targets
  - distribution
    - solid urea could help
  - tampering
    - NOx sensors
    - quick on-the-road diagnostics
  - ammonia slip is addressed with oxidation catalysts
- NOx Traps are the silver bullet
  - sulfur needs to be very low (<10 ppm light duty, perhaps lower for heavy duty)
  - or sulfur traps need to be developed
  - regeneration and desulphation schemes are in the works



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